

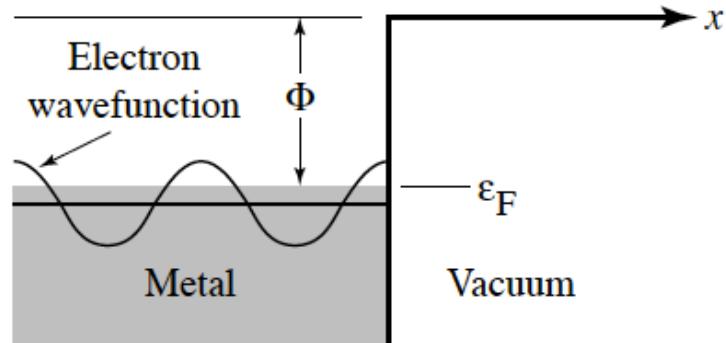
Overview of field emission problem in SRF cavities

A. Romanenko

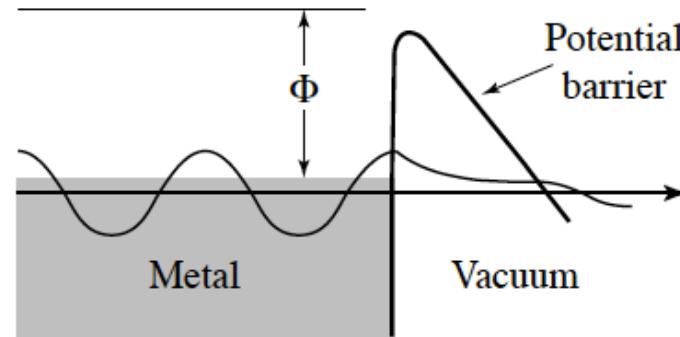
Outline

- Field emission problem
 - Theoretical description
 - Mitigation
 - Statistical model
- Expectations for Project X based on state-of-the-art (ILC)
- SNS experience
- Conclusions

Theory of field emission



No external field



External E-field applied

Quantum tunneling of electrons through the potential barrier, tunneling current given by Fowler-Nordheim equation:

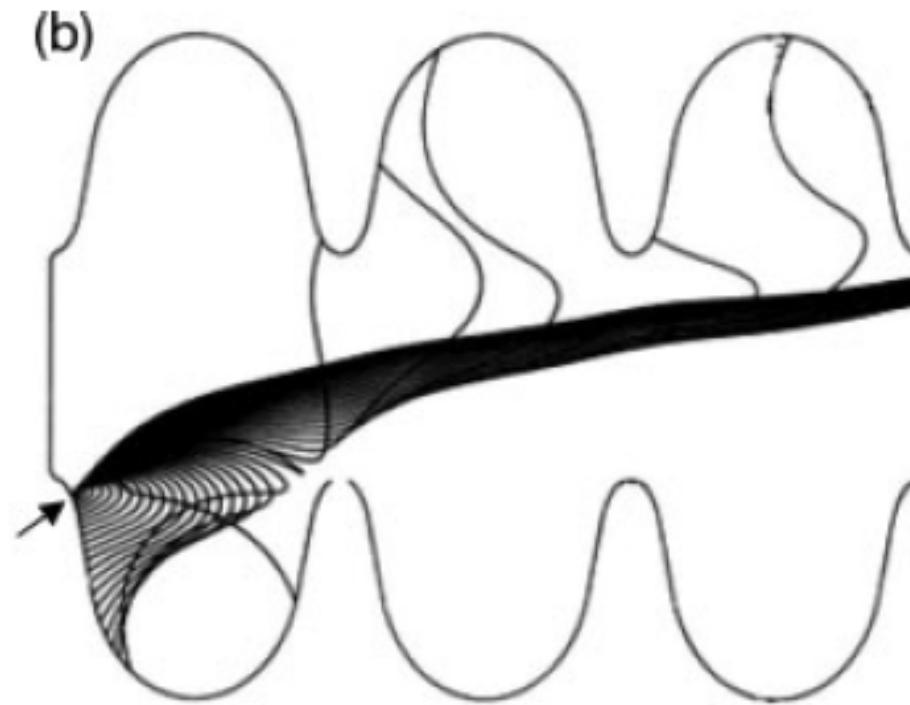
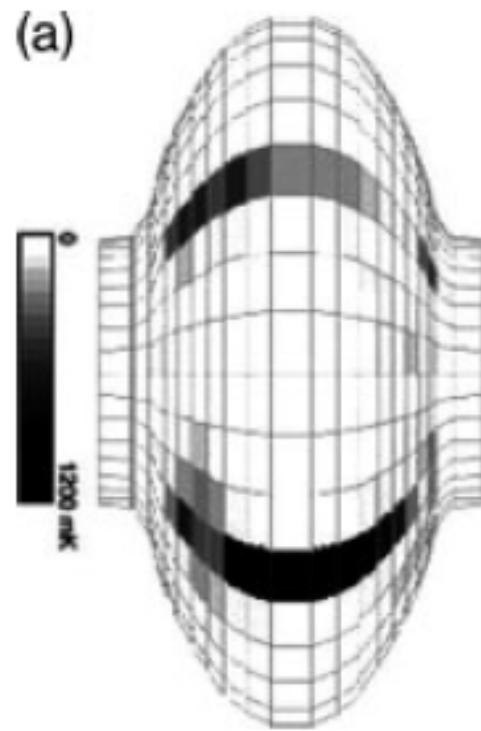
$$I_{FN} = \text{const} * A_{FN} * E^2 * \exp(-\text{const}/E)$$

A_{FN} – effective emitter area

For niobium FN equation has to be modified: $E \rightarrow \beta_{FN}E$

β_{FN} – electric field enhancement factor

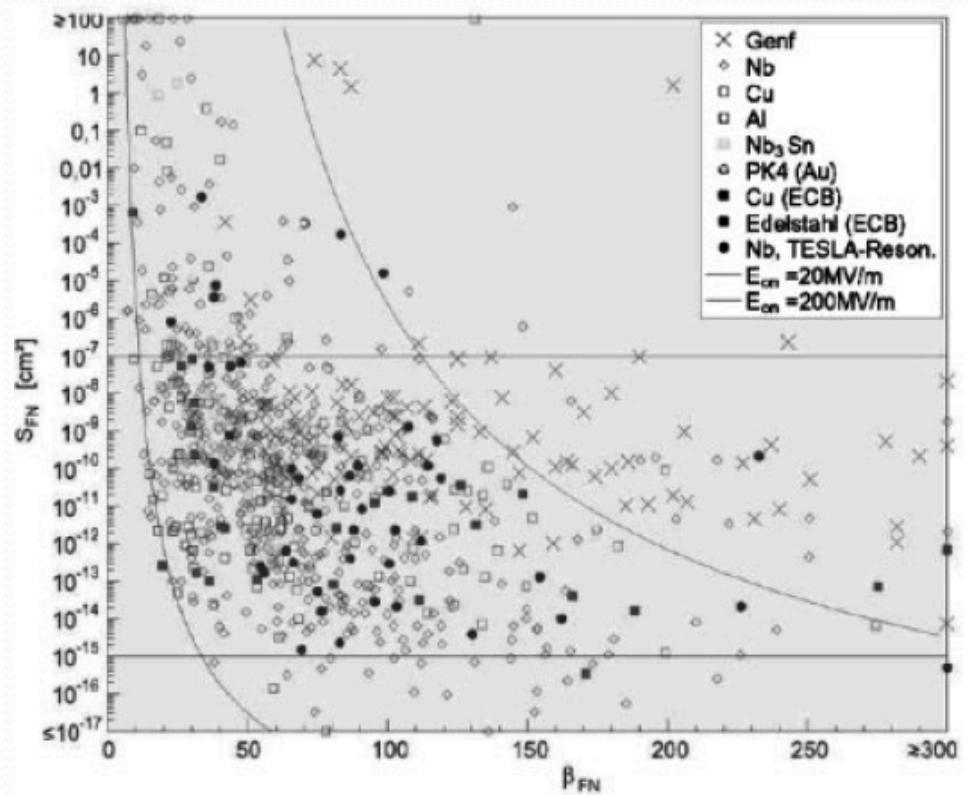
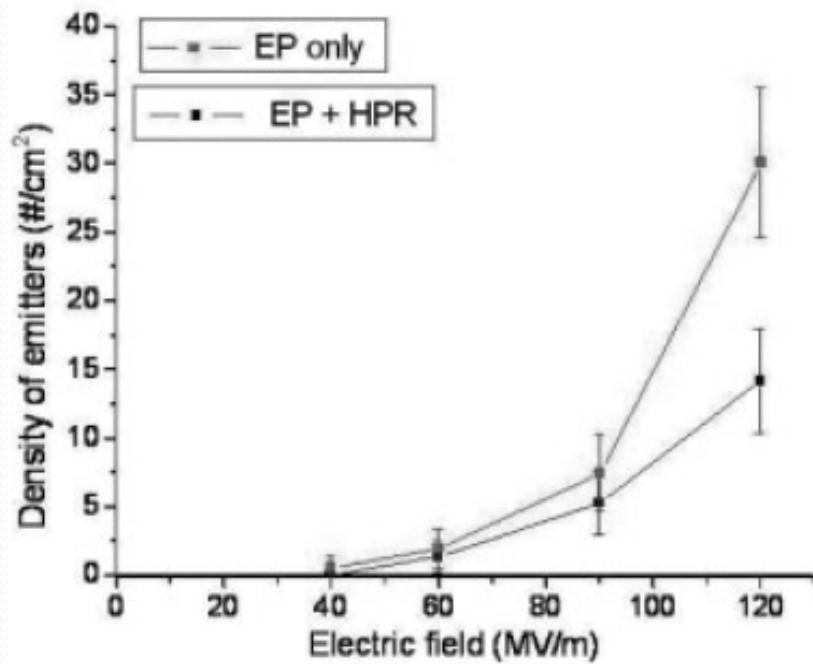
Field emission in cavities



Particular pattern in
temperature maps –
line heating

Example of calculated trajectories for
emitted electrons in a 3-cell 1.5 GHz cavity

DC studies of field emitters

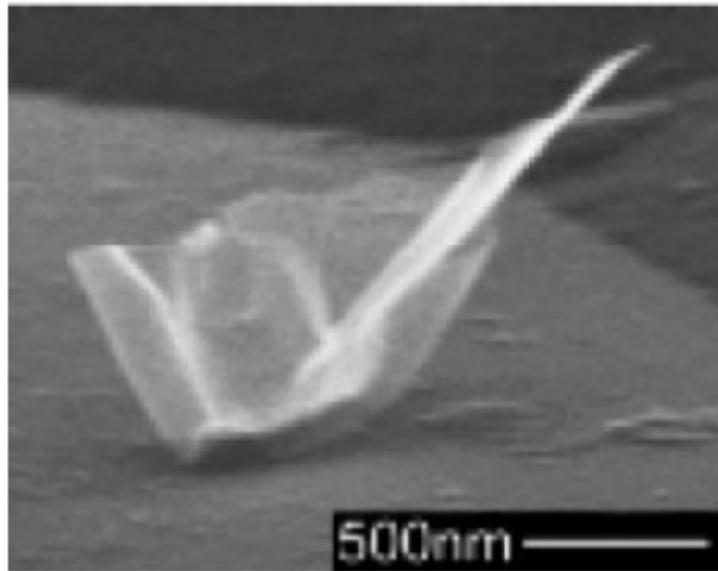


A. Dangwal, Proceedings of SRF'05

T. Habermann, PhD Thesis, Univ. Wuppertal

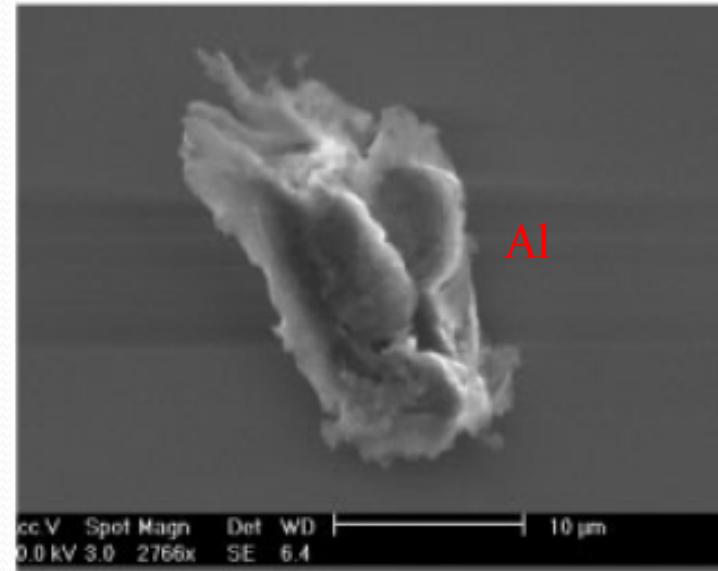
DC studies: nature of field emitters

Emitter from sample processed with TESLA 9-cells



G. Muller, Proceedings of EPAC'98

DC field emission scan identified particle



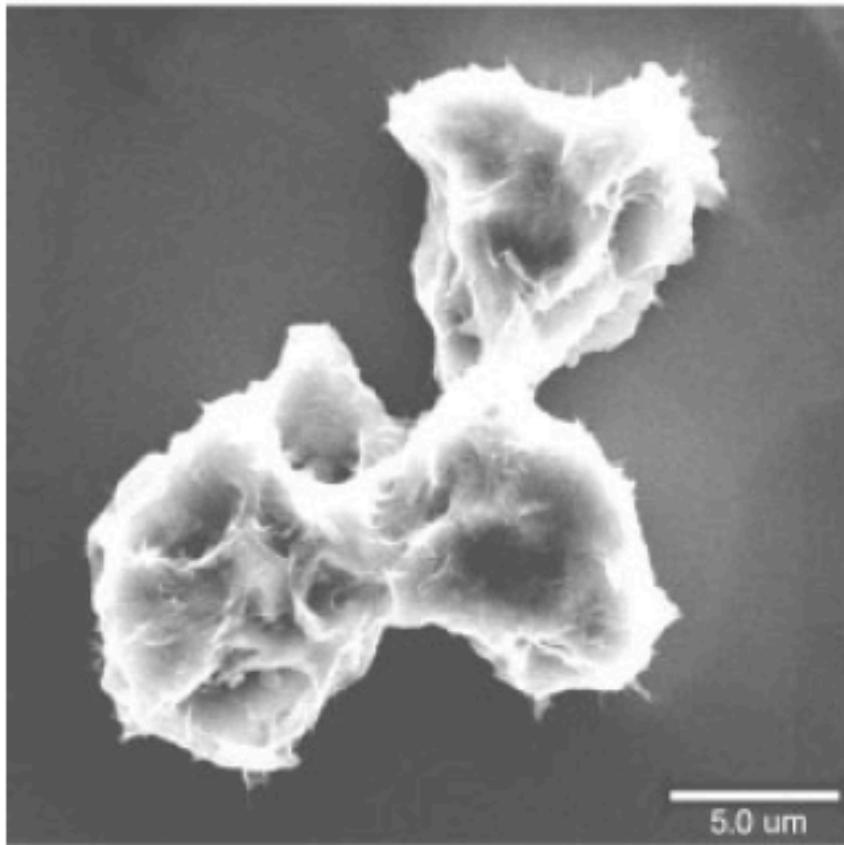
A. Dangwal, Proceedings of SRF'05

Field emitters are predominantly microparticles

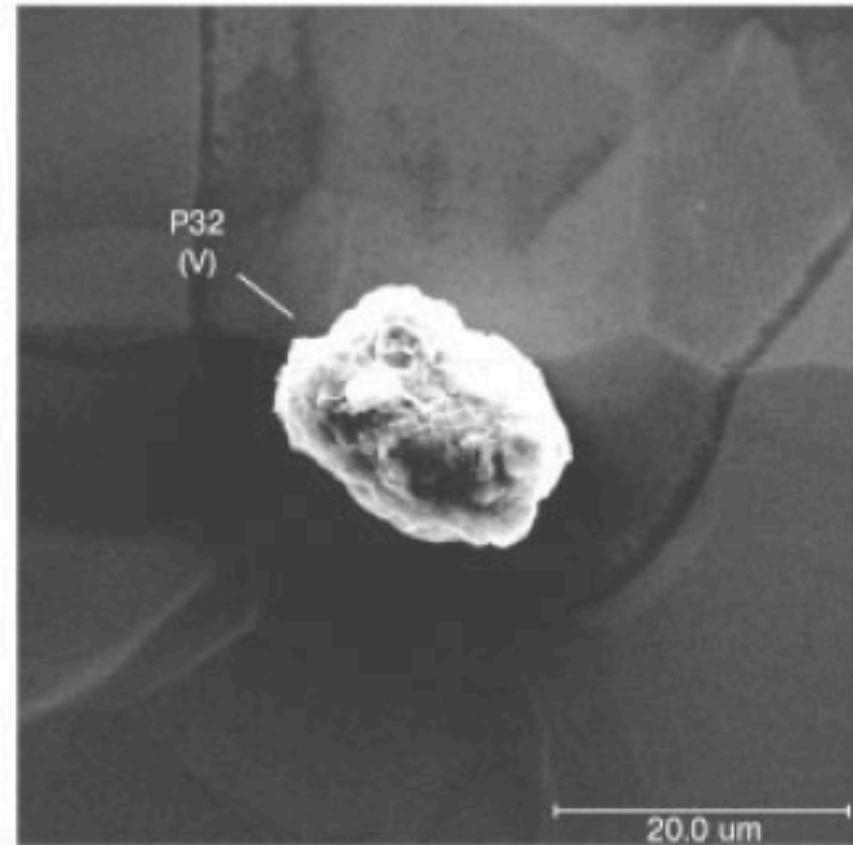
Scratches with sharp edges may be field emitting too

DC studies: field enhancement

G. Werner, Proceedings of PACo1



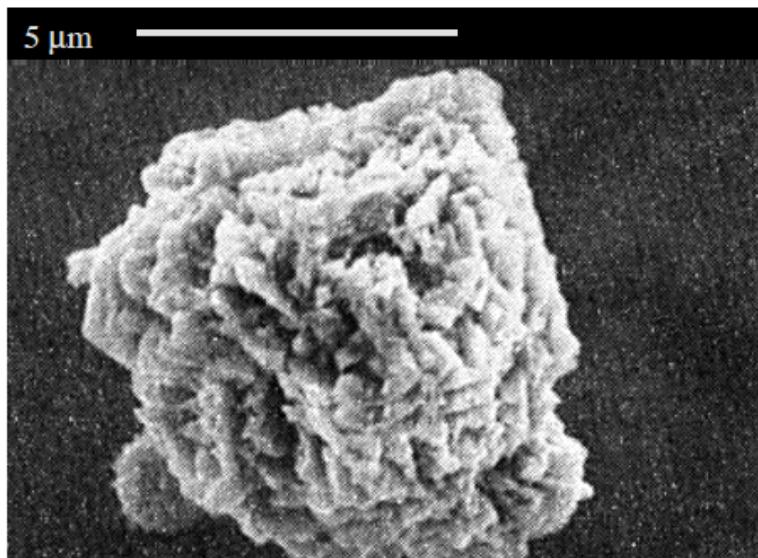
$E_{bd}=40 \text{ MV/m}$



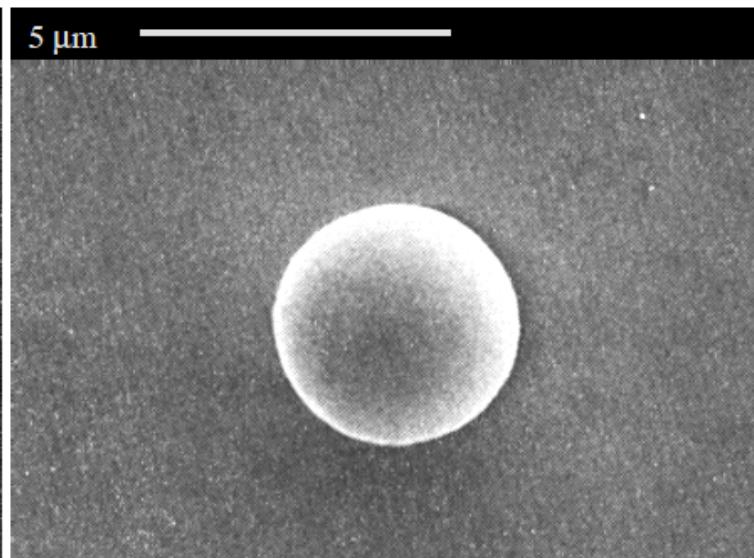
$E_{bd}>100 \text{ MV/m}$

Typical field emitters

- Multiple DC field emission and voltage breakdown studies indicate – field emission depends on the presence of sharp features

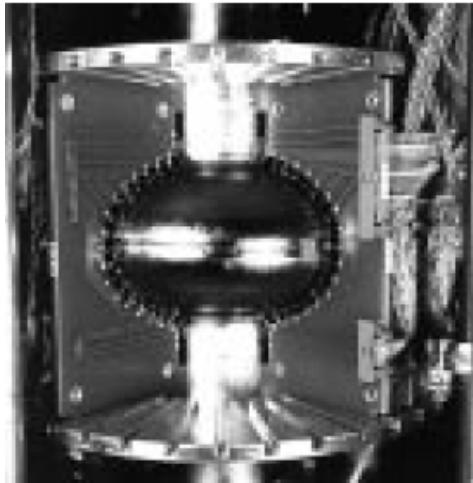


Emitting

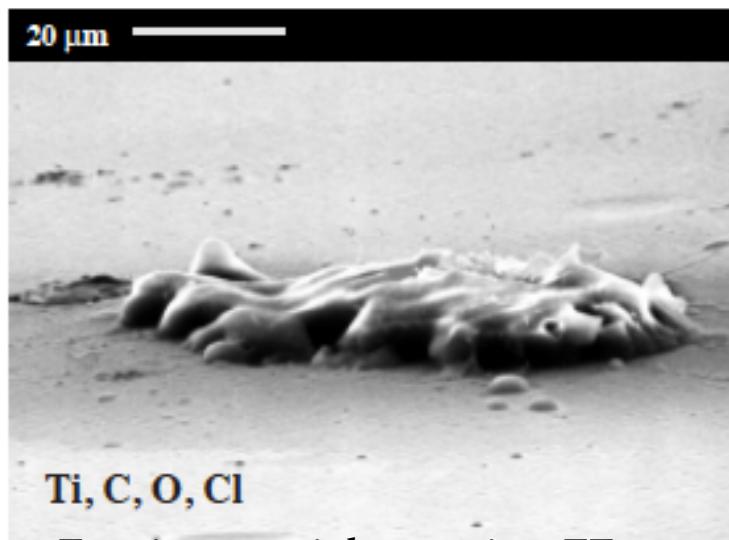


Not emitting up to 100 MV/m

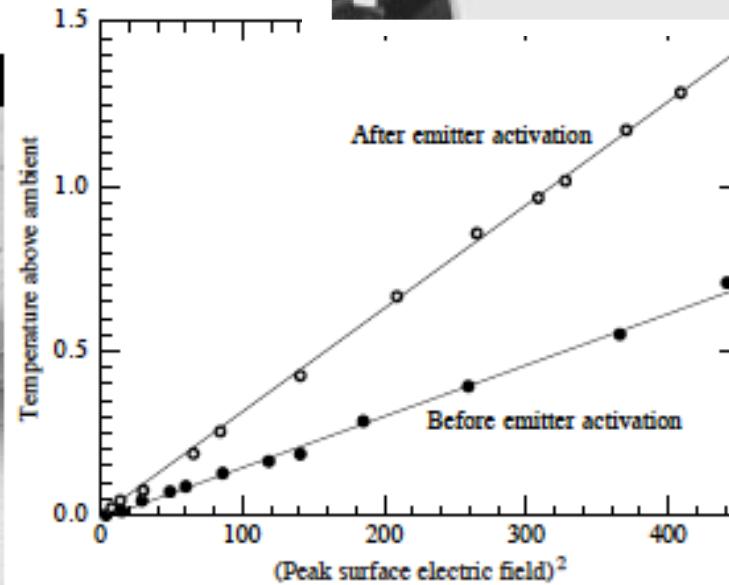
- Extensive investigation on cavities – [J. Knobloch, PhD thesis, Cornell University, 1998]



Thermometry identifies field emission sites during RF tests



Foreign particle causing FE

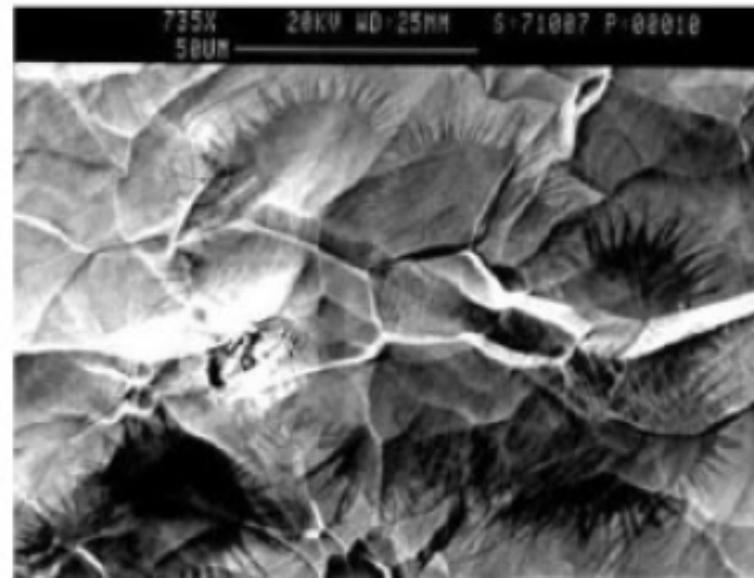


SEM/EDX investigations of dissected cavities reveal the source of FE



RF processing

- CW helium processing
 - Introduce He gas in the cavity ($P \sim 10^{-5}$ Torr)
- High Pulsed Power (HPP) processing
 - ~a few 100 microsecond pulses of high (~ 1 MW power)



Statistical model

[H. Padamsee et al, Proceedings of PAC93]

Parameters:

A_e = effective emitter area

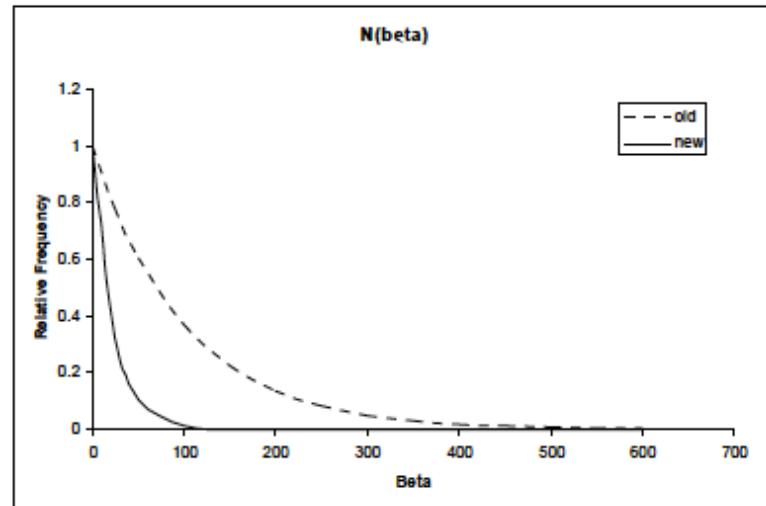
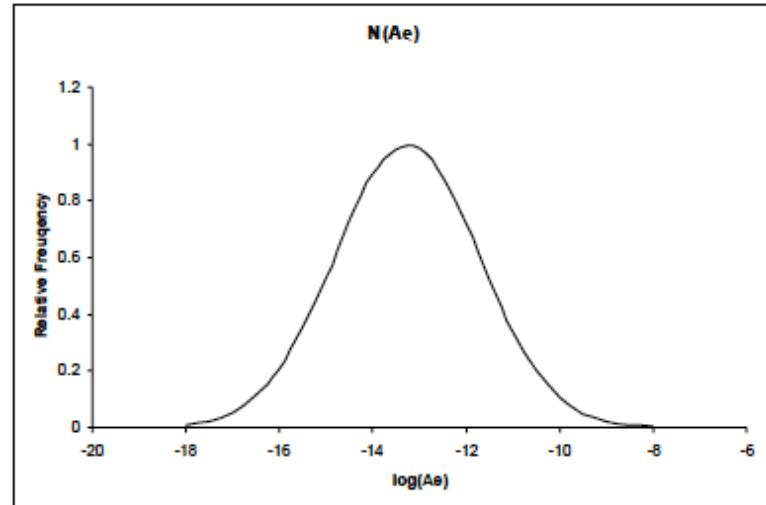
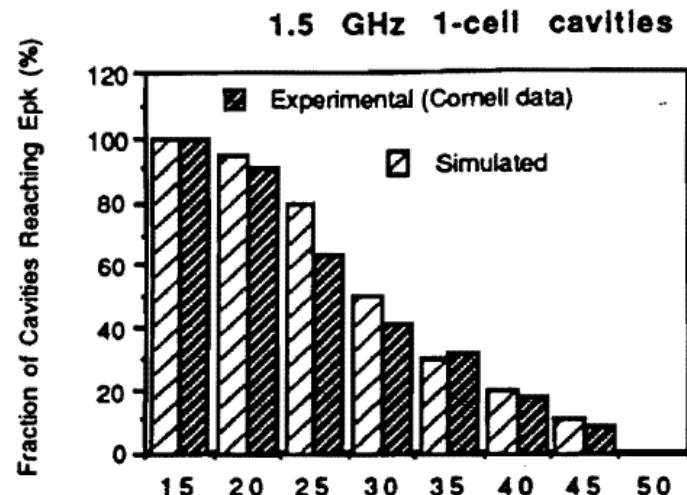
β = field enhancement factor

$$N(\beta) \sim \exp(-0.01 * \beta)$$

$$N(Ae) \sim \exp\{-([\log(Ae) + 13.262]/2.175)^2\}$$

Power dissipated per emitter

$$P = Ae * 10^{12} * (1500/freq)^{1.5} * 1.8 \times 10^7 * \exp(-7.4 \times 10^4 / \beta E)$$



Single parameter – average emitter density

SNS

Table 1: SNS cavities' electromagnetic parameters.

Cavity β	0.61	0.81
Frequency [MHz]	805.000	805.000
$E_{\text{peak}}/E_{\text{acc}}$	2.71	2.19
$B_{\text{peak}}/E_{\text{acc}}$ [mT/(MV/m)]	5.72	4.72
R/Q [Ω]	279	483
$G (=R_s Q_0)$ [Ω]	179	260
Cell-to-cell k [%]	1.53	1.52
K_L [Hz/(MV/m) 2]	-2.07	-0.43

[G. Giovati et al, Proceedings of PAC01]

Project X

Table 3: RF parameters of the 650 MHz cavities.

Geometrical β	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV(on crest)	11.7	17.5
Gradient, MeV/m	16.6	16.9
Max. surf. electric field, MV/m	37.5	33.7
$E_{\text{pk}}/E_{\text{acc}}$	2.26	2
Max surf. magnetic field, mT	70	63
$B_{\text{pk}}/E_{\text{acc}}$, mT/(MeV/m)	4.21	3.75

[V. Yakovlev et al, Proceedings of PAC11]

ILC

Parameter	Value
Type of accelerating structure	Standing Wave
Accelerating Mode	TM ₀₁₀ , π mode
Fundamental Frequency	1.300 GHz
Average installed gradient	31.5 MV/m
Qualification gradient	35.0 MV/m
Installed quality factor	$\geq 1 \times 10^{10}$
Quality factor during qualification	$\geq 0.8 \times 10^{10}$
Active length	1.038 m
Number of cells	9
Cell to cell coupling	1.87%
Iris diameter	70 mm
R/Q	1036 Ω
Geometry factor	270 Ω
$E_{\text{peak}}/E_{\text{acc}}$	2.0
$B_{\text{peak}}/E_{\text{acc}}$	$4.26 \text{ mT MV}^{-1}\text{m}^{-1}$
Tuning range	± 300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Number of HOM couplers	2

$$A_{\text{PX}}/A_{\text{ILC}} \sim 4 - \text{cavity surface area}$$

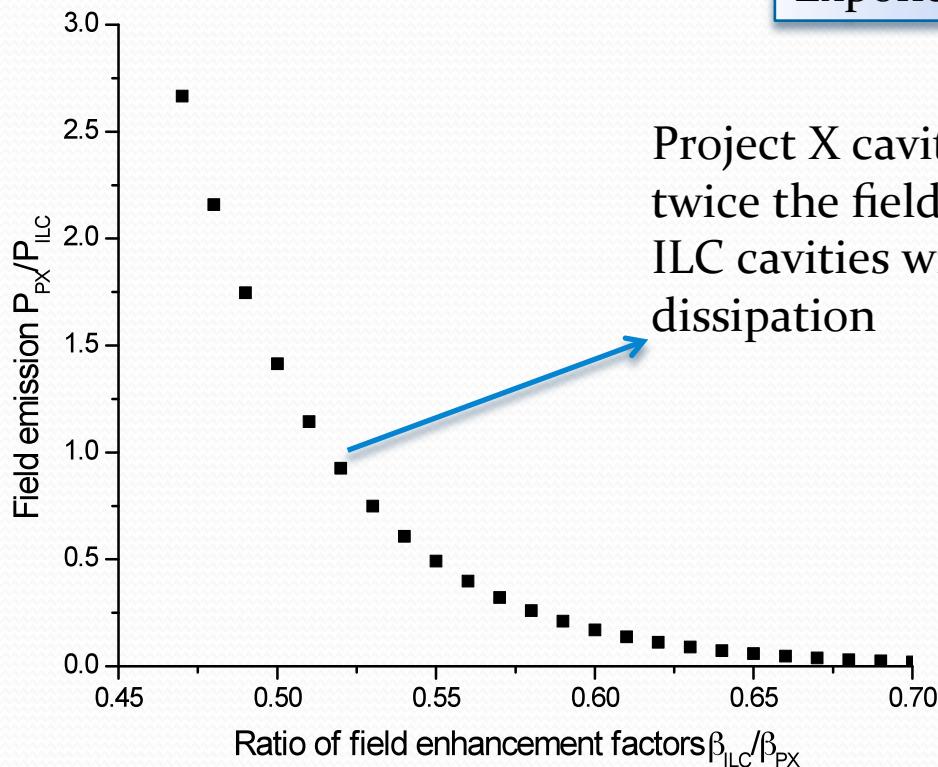
$$E_{\text{peak, ILC}}/E_{\text{peak, PX}} \sim 2$$

Simple estimates

$$P_{FE} = \text{const} * N_{\text{emitters}} * (1500/f)^{1.5} * \exp\{-7.4*10^4/(\beta_{FN}E)\}$$

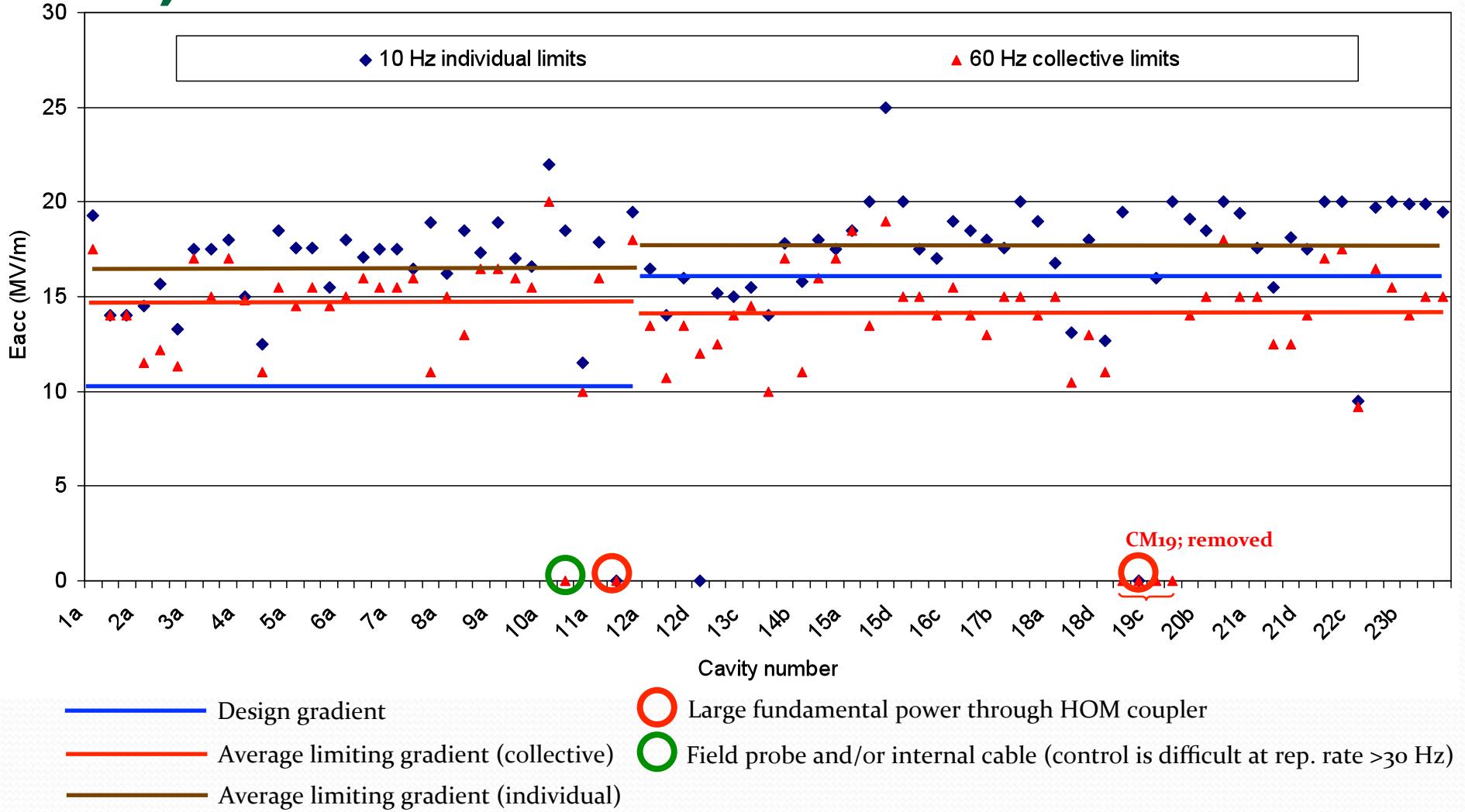
$$P_{PX}/P_{ILC} = A_{PX}/A_{ILC} * (650/1300)^{1.5} * \exp\{-7.4*10^4/(\beta_{ILC}E_{\text{peak, } PX}) * (\beta_{ILC}/\beta_{PX} - 1/2)\}$$

Exponential term is dominant

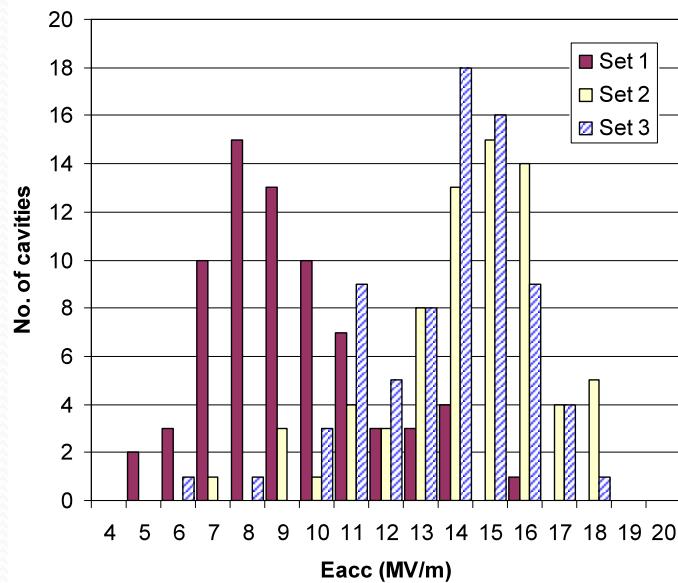


Project X cavities can tolerate up to twice the field enhancement factor of ILC cavities with the same power dissipation

Limiting gradients and statistics ('06-'07 data)



Cryogenic loads at SNS

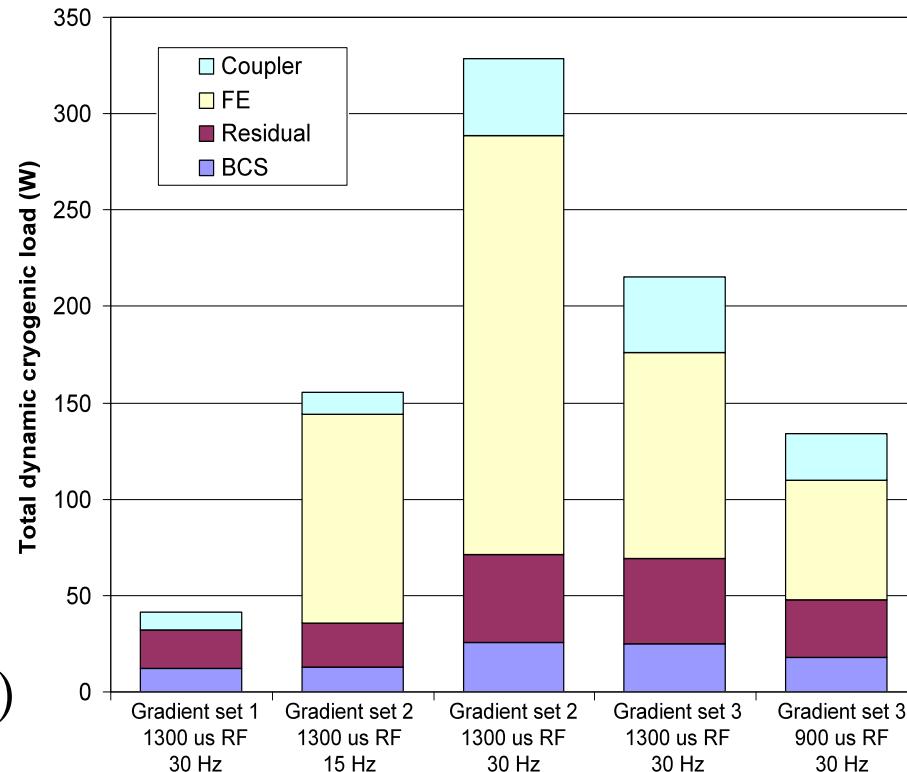


Set 1; Below FE threshold (~9MV/m)

Set 2; 80 % of individual limits

Set 3; 88 % of collective limits

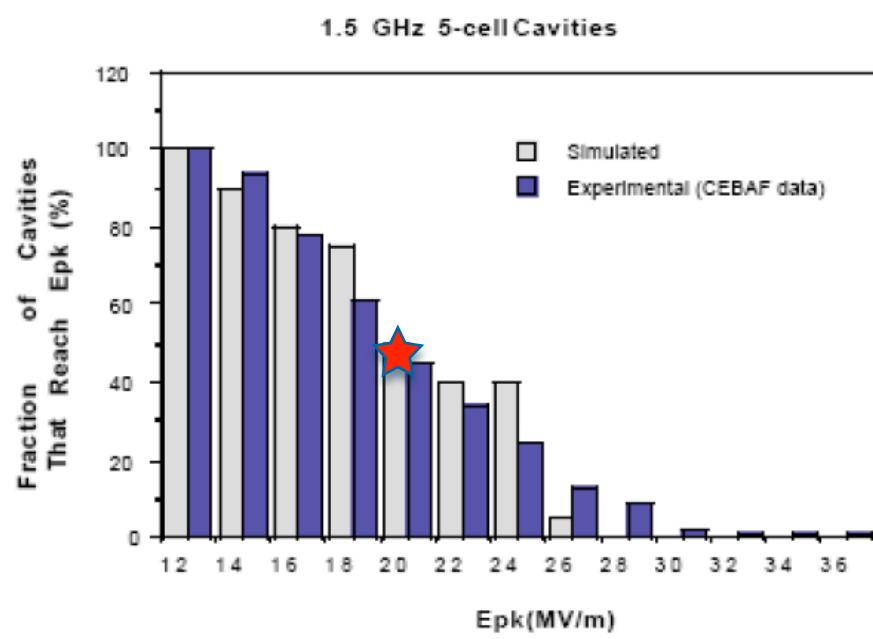
Avg(set3)-Avg(set2)~1MV/m



Total dynamic heat loads due to different sources

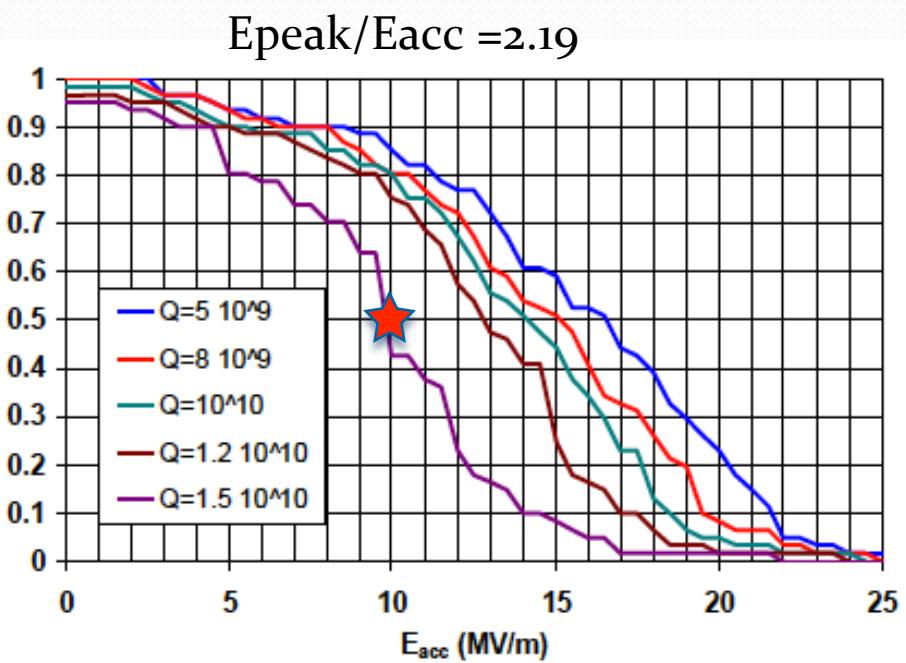
[H. Padamsee et al, Proceedings of PAC93]

Data on CEBAF cavities – NO HIGH PRESSURE RINSE



[J. Delayen, J. Mammoser, J. P. Ozelis, Proceedings of PACCo5, TPPTo79]

Data on SNS beta=0.81 cavities – vertical test results at Jlab



Yield curve for SNS cavities is similar to CEBAF cavities
WITHOUT high pressure rinsing – poor HPR effectiveness!

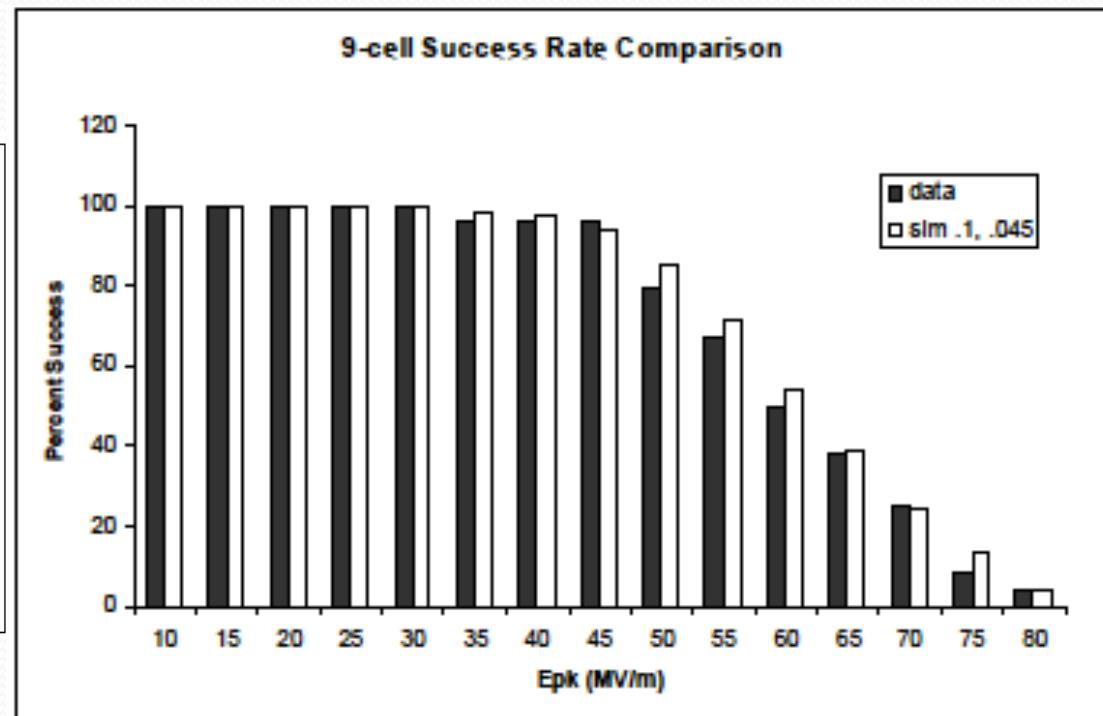
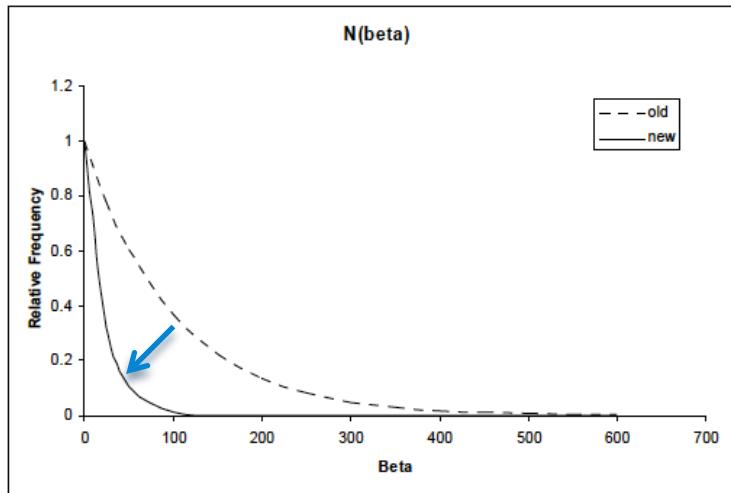
Improvements to mitigate FE

- Clean room class 10-100 assembly
- Minimization of exposure to possible contamination sources
- High pressure ultrapure water rinsing
 - 100 bar water jet removing particles adhered to the surface

Recent processing improvements

Statistical model – narrower beta distribution is necessary

$$N(\beta) \sim \exp(-0.045\beta)$$



Many newer developments to improve even further – ultrasonic degreasing, ethanol rinsing, dry ice cleaning

[J. Wiener, H. Padamsee, Proceedings of EPACo8, MoPP164]

DESY data on 24 9-cell tests

Conclusions

- Field emission is a well understood phenomenon
- Most field emitters – microparticles on the surface
- Ways to avoid: clean room assembly, high pressure water rinsing
- In situ mitigation: helium processing, high power pulse processing
- Recent technology advances demonstrated significant field emission reduction in ILC cavities
 - Project X does not have to be similar to SNS with respect to field emission (technology >10 years ahead)